

## HIGGS SEARCHES AT THE TEVATRON\*

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### Abstract

Higgs hunting is a world-wide sport and the Tevatron is set to become the next field of play when Run II starts in March 2001. To set the stage, we summarize results of searches for standard and non-standard Higgs bosons by CDF and DØ in Run I at the Tevatron. Progress has been made in quantifying the requirements on the Tevatron Collider and on the upgraded experiments in Run II for extending the excellent work done at LEP. Armed with parameterizations of expected detector performance, the Tevatron Higgs Working group has made predictions of the sensitivity of CDF and DØ to Higgs bosons in the Standard Model and in its Minimal Supersymmetric extension as a function of integrated luminosity. These predictions are presented to underscore the excitement being generated by Run II, and to highlight the need for the highest possible luminosity.

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# 1 Introduction

Despite increasingly precise scrutiny, the standard model (SM) of particle physics remains largely unshaken. Only the recent experimental evidence for massive neutrinos<sup>1)</sup> challenges any of its many predictions. With the single exception of the Higgs boson, all the particles expected in the SM, and no others, have now been observed. This single missing particle represents a major gap in our knowledge of the microscopic world. Tied up in its nature (or natures, in the case that there is more than one Higgs scalar) is the method by which the original  $SU(2)_L \times U(1)$  symmetry of the theory is spontaneously broken to the distinct electromagnetic and weak forces we observe.

Within the SM, the mass of the single physical Higgs boson left after electroweak symmetry breaking is related to the vacuum expectation value of the neutral Higgs field ( $v = 246$  GeV) by  $M_h^2 = \lambda v^2$ . The Higgs self-coupling parameter,  $\lambda$ , is not specified by the theory, making the Higgs mass an unknown quantity. However, if the Higgs mechanism is to fulfill its role in the SM, the Higgs mass cannot exceed 1 TeV, otherwise unitarity would be violated in the scattering of longitudinally polarized gauge bosons.

Since it does not incorporate gravity, the SM cannot be a fundamental theory of all interactions despite its many other successes. Even if it is a correct effective theory up to the Planck scale of  $\sim 10^{19}$  GeV, where quantum gravitational effects become significant, the SM is still unsatisfying. This is because radiative corrections to the square of the Higgs mass are quadratically divergent in an energy cutoff parameter, which should be the Planck scale if the SM is to be valid up to that range. In order to get a physical Higgs mass on the order of the electroweak scale, these corrections must be cancelled by tuning the bare Higgs mass at the Planck scale to one part in  $10^{16}$  – a rather unnatural condition.

Since there is an implied need for new physics beyond the SM, a natural question to ask is at what energy scale ( $\Lambda$ ) should such effects become apparent. The physics would then look SM-like below  $\Lambda$ , but new particles and interactions would become apparent beyond that scale. This question is intimately related to the mass of the Higgs boson that is used to break electroweak symmetry. At large values of  $M_h$ , the renormalization group equation for the Higgs self-coupling causes  $\lambda$  to blow up for  $\Lambda$  below the Planck mass. The point at which this happens then sets the scale for new physics. On the other hand, if  $M_h$  is too small, top quark contributions to  $\lambda$  can drive it negative. To avoid this problem an energy cutoff must be introduced that can be associated with  $\Lambda$ . Using these constraints, a measurement of the Higgs

mass at the relatively low energies of today's accelerators could clarify the scale for the breakdown of the SM.

Many theoretical frameworks have been proposed to address some of the weaknesses of the SM without abandoning its low energy successes. These will not be discussed here. We will limit our discussion to results of the minimal supersymmetric standard model (MSSM) <sup>2)</sup>, a guide indicative of extensions that probe the nature of physics and the Higgs beyond the SM.

The MSSM is the simplest version of supersymmetric models that solve the “naturalness” problem discussed above by relating fermionic and bosonic degrees of freedom <sup>3)</sup>. This involves adding supersymmetric partners to all SM particles that differ from their SM counterparts by a half unit of spin. An additional requirement is the expansion of the Higgs sector to include more than the single complex doublet used in the SM. The MSSM proposes only a single extra complex doublet. After electroweak symmetry breaking, five physical Higgs particles remain: two CP-even neutral scalars,  $h$  and  $H$  (with  $M_h < M_H$  by convention), one CP-odd neutral scalar  $A$  and two charged scalars  $H^\pm$ .

The parameters of the MSSM that most directly affect the Higgs bosons are  $\tan \beta$  (the ratio of the vacuum expectation values of the two Higgs doublets) and  $M_A$  (the mass of the CP-odd Higgs, conventionally chosen to be the free Higgs mass in the theory). Unlike the case of the SM, in the MSSM, the mass of the lightest of the Higgs bosons,  $h$ , is constrained by supersymmetry. At tree level, this mass must be less than that of the  $Z^0$ . Radiative corrections modify this relationship, but an upper bound still exists with  $(M_h)_{\max} \sim 130$  GeV.

The mass of an SM-like Higgs is also constrained by experimental measurements. Direct searches at LEP 2 currently give the most stringent lower bound on the mass. This bound changes as LEP accumulates more data. A snapshot of the LEP-wide 95% C.L. limit given at the September 1999 LEPC <sup>4)</sup> constrains  $M_h > 102.6$  GeV. The best experimental upper bound on the Higgs mass comes from global fits to electroweak measurements done by the LEP Electroweak Working Group. Their results <sup>5)</sup> indicate that  $M_h < 215$  GeV at 95% C.L.

## 2 The Higgs at the Tevatron

If a Higgs boson is not discovered at LEP 2 in its last year of running, the next place to look will be the Tevatron at Fermilab. The Tevatron is a  $\bar{p}p$  collider that operated until 1996 at a center of mass energy of  $\sqrt{s} = 1.8$  TeV. Two experiments, CDF <sup>6)</sup> and DØ <sup>7)</sup>, each collected approximately  $100 \text{ pb}^{-1}$  of data during the period 1992–

1996. As we will see, this data set, referred to as “Run I” data, is not sufficiently large to have competitive sensitivity to an SM Higgs although interesting studies have been made in certain non-standard models.

Not content with the success of Run I, the Tevatron accelerator is being upgraded to increase its center-of-mass energy to  $\sqrt{s} = 2.0$  TeV and to ultimately achieve an instantaneous luminosity of  $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$  8). CDF 9) and DØ 10) are also being upgraded to take advantage of the higher luminosity. Data taking for this new “Run II” will start in March 2001. Projections for integrated luminosity in Run II begin at  $2 \text{ fb}^{-1}$ , but could reach another factor of ten. Obviously, with this large expected data set, CDF and DØ have a bright future.

Before we dive into the details of Run I Higgs searches and projections for Run II sensitivities, it is worthwhile to review how Higgs bosons are produced and decay, and how they would be detected at the Tevatron. The cross section for SM Higgs bosons in  $\bar{p}p$  collisions, as calculated by Spira 11), is given in Fig. 1 for various production modes. The main SM Higgs decay modes, calculated using the program HDECAY 12), are given in Fig. 2 13) as a function of Higgs mass. Corresponding plots for the neutral MSSM Higgs bosons,  $h$ ,  $H$  and  $A$ , also based on the calculations by Spira, are available on the Fermilab Run II Higgs Working Group web page 13). These have largely similar characteristics to the plots for SM Higgs, however, at large  $\tan\beta$  couplings to  $b$ -quarks and  $\tau$ -leptons are enhanced, leading to  $h(H)b\bar{b}$  production being favored over the  $h(H)W/Z$  modes.

The clear advantage of the Tevatron over  $e^+e^-$  machines is its center of mass energy – a factor of 10 higher than at LEP. Of course, not all of this energy is available to the partons participating in the hard scattering producing the Higgs. Nevertheless, higher mass Higgs bosons can be produced at the upgraded Tevatron than at any previous machine. The problem is finding them.

Table 1 spells out the difficulty in identifying a Higgs at the Tevatron – the immense background. Clearly, the most favorable production mode for the SM Higgs,  $gg \rightarrow h_{SM}$  (through intermediate top quarks), cannot be used in a search for a low mass Higgs ( $M_h < 130$  GeV), that decays mainly to  $b\bar{b}$ . Background from QCD dijet production is a factor of  $\sim 10^6$  larger than the signal. This has prompted Tevatron Higgs hunters to concentrate on the next highest cross section production modes of a light Higgs in association with a W or Z. Even here, searches must contend with difficult background from boson-pair,  $W/Zb\bar{b}$  and top quark production.

If the Higgs has higher mass, identification is slightly easier although the production cross section is smaller because decays to WW and ZZ begin to dominate above  $M_h \sim 130$  GeV. In fact, these unique final states, make it possible to take

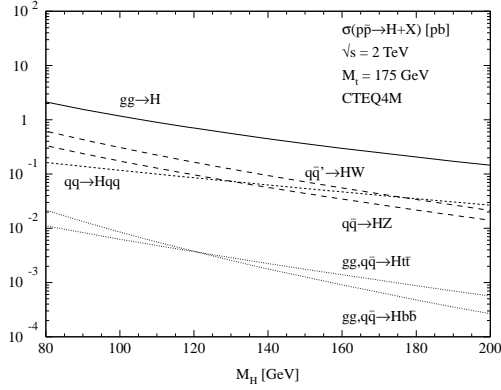


Figure 1: *Production cross-sections in  $p\bar{p}$  collisions at  $\sqrt{s} = 2.0$  TeV for various SM Higgs modes as a function of Higgs mass <sup>11)</sup>.*

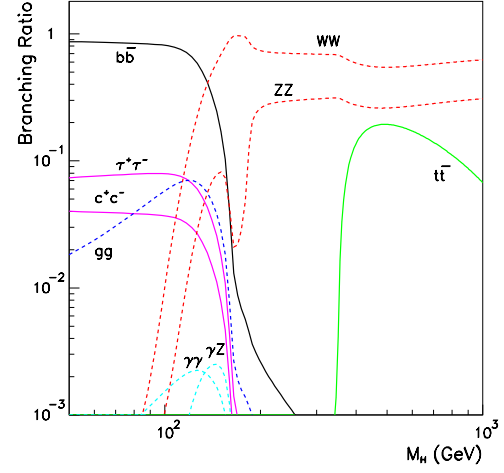


Figure 2: *Branching ratios for the SM Higgs as a function of Higgs mass <sup>13)</sup>.*

Table 1: *Representative cross sections for SM Higgs production ( $M_h = 100$  GeV) and some major backgrounds <sup>13)</sup>.*

Mode	Cross-Section [pb]
$gg \rightarrow h_{SM}$	1.0
$Wh_{SM}$	0.30
$Zh_{SM}$	0.17
$WZ + ZZ$	4.4
$Wb\bar{b} + Zb\bar{b}$	14
$t\bar{t}$	7.5
$tb + tq + tbq$	3.4
QCD di-jet	$\mathcal{O}(10^6)$
QCD four-jet	$\mathcal{O}(10^4)$

advantage of the  $gg \rightarrow h_{SM}$  production mode in this mass region.

Regardless of the mass of the Higgs, searches at the Tevatron will take advantage of all distinguishing features of Higgs decay to overcome backgrounds with cross-sections many times larger than those of the Higgs. The most promising final states for a low mass SM Higgs (that decays mainly to  $b\bar{b}$ ) are:  $\ell\nu b\bar{b}$ ,  $\ell^+\ell^-b\bar{b}$ ,  $\nu\bar{\nu}b\bar{b}$  and  $jjb\bar{b}$ . For a high mass SM Higgs (decaying mainly to WW/ZZ) the best final states contain the following distinguishing particles:  $\ell^+\ell^-\nu\bar{\nu}$ ,  $\ell^\pm\ell^\pm jj$  and  $\ell^\pm\ell'^\pm\ell'^\mp$ . Discussion of the motivation for choosing these final states can be found in Run II Higgs Working Group Report <sup>13)</sup>.

A few themes emerge from consideration of Table 1 and the final states listed above. To be maximally sensitive to the Higgs, an ideal Tevatron detector must have all of the following properties:

1. High lepton (e and  $\mu$ ) identification efficiency,
2. Excellent missing energy resolution (for neutrino identification),
3. High  $b$ -quark identification efficiency,
4. Good invariant mass resolution for  $b\bar{b}$  pairs (to reject  $b\bar{b}$  background outside of the  $h_{SM} \rightarrow b\bar{b}$  peak).

The same signatures mentioned for the SM Higgs will also be important for finding neutral Higgs scalars in the MSSM. Since couplings to  $b$ -quarks and  $\tau$ -leptons tend to grow with increasing  $\tan\beta$ ,  $\tau$  identification takes on greater importance and good sensitivity to  $b$  jets becomes even more crucial.

An MSSM charged Higgs with mass less than  $m_t - m_b$  is expected to be produced at the Tevatron through the decay of top quarks – a very different mechanism than for neutral Higgs particles. In regions of large and small  $\tan\beta$  (away from  $\tan\beta \sim 6$ ) the branching ratio for  $t \rightarrow H^\pm b$  is predicted to be quite large. The decay of the  $H^\pm$  is mainly to  $Wb\bar{b}$  and  $cs$  for low  $\tan\beta$  and to  $\tau\nu_\tau$  for high  $\tan\beta$ . These final states are sufficiently different from the SM top-quark decays that standard top analyses would have low efficiency for them. This means that, in addition to looking explicitly for the  $H^\pm$  decay products (especially  $\tau\nu$ ) a “disappearance” search is also possible for  $H^\pm$ . For a substantial branching ratio of top to charged Higgs, the measured  $p\bar{p} \rightarrow t\bar{t}X$  cross-section would be smaller than the SM expectation. A discrepancy between measurement and prediction can provide evidence for  $H^\pm$ .

Table 2: A summary of results of Run I Higgs searches by CDF and DØ. Production cross-section multiplied by the  $h_{SM} \rightarrow b\bar{b}$  branching ratio ( $\sigma \times B$ ) limits are for a 100 GeV Higgs, where  $B \sim 0.81$ . Values marked with an asterisk are preliminary.

Channel	Contributing Modes	Predicted $\sigma \times B$ [pb]	95% C.L. Limits	
			CDF	DØ
$\sigma \times B$ Limits [pb]				
$\ell\nu b\bar{b}$	$Wh_{SM}$	0.24	$<27^{14)}$	$* <28^{15)}$
$jjb\bar{b}$	$Wh_{SM}+Zh_{SM}$	0.38	$<23^{14)}$	—
comb.	$Wh_{SM}+Zh_{SM}$	0.38	$<17^{14)}$	—
$\nu\bar{\nu}b\bar{b}$	$Zh_{SM}$	0.14	$* <8$	$* <\mathcal{O}(70)^{16)}$
$\ell^+\ell^-b\bar{b}$	$Zh_{SM}$		$* <38$	—
comb.	$Zh_{SM}$		$* <7.5$	—
$b\bar{b}b\bar{b}$	$\phi b\bar{b}$	$0.01\cdot\tan^2\beta$	$* <26$ pb	—
$M_h$ Limits [GeV]				
$\gamma\gamma X$	$h\rightarrow\gamma\gamma$	0.07	$* >82^{17)}$	$>78.5^{18)}$
$B(t\rightarrow H^\pm b)$ Limits				
$t\bar{t}$ -disappearance	$t\rightarrow H^\pm b$		$* <32\%^{19)}$	$<45\%^{20)}$
$(\ell\ell)/(\ell+j)$	$t\rightarrow H^\pm b\rightarrow csb$		$* <72\%^{19)}$	—
$\tau\ell j$	$t\rightarrow H^\pm b\rightarrow\tau\nu b$		$<60\%^{21)}$	—
$M_{H^\pm}$ Limit [GeV]				
$\tau jjX+2\tau$	$t\rightarrow H^\pm b\rightarrow\tau\nu b$		$>147^{22)}$	—

### 3 Higgs Searches at Run I

Searches for Higgs have been performed by CDF and DØ in all the main SM final states as well as in models beyond the SM. Results are summarized in Table 2. The reach of CDF and DØ in production cross-section multiplied by  $h_{SM} \rightarrow b\bar{b}$  branching ratio in standard Higgs modes is far weaker than the predictions of the SM. For certain models beyond the SM, however, sizable regions of parameter space can be excluded. The charged Higgs of the MSSM is an especially interesting search since the Tevatron is the only facility that can take advantage of the  $t \rightarrow H^\pm b$  mode.

### 3.1 The Four- $b$ Final State at CDF

A preliminary analysis from CDF is another good example of the possibilities of Run I searches in beyond-the-SM scenarios. Here,  $b$ -quark identification of the CDF detector is used to select events with four  $b$  jets in the final state. This topology is expected at large  $\tan\beta$  in several SUSY models where the coupling of some of the neutral Higgs scalars to  $b$ -quarks is enhanced<sup>23)</sup>. The final state arises in  $b\bar{b}$  production when one of the primary  $b$ -quarks radiates a neutral Higgs which, then decays to  $b\bar{b}$ . The cross section for this process goes as  $\tan^2\beta$ , and can therefore become sizable at large  $\tan\beta$ . The cross section is also affected by details of the mixing between left- and right-handed stop squarks. Results are presented for two extreme cases: that of minimal and maximal stop mixing.

This CDF analysis, which is an update of that presented in the Run II Higgs Working Group Report<sup>13)</sup>, uses a multijet trigger requiring a total cluster energy of  $>125$  GeV and at least four trigger clusters with energy  $>15$  GeV for an integrated luminosity of  $91\text{ pb}^{-1}$ . Offline, at least four jets are required, with  $E_T \geq 15$  GeV and  $|\eta| < 2.4$ <sup>1</sup>. Three of these jets must be tagged by the CDF secondary vertex algorithm<sup>24)</sup> as arising from  $b$ -quarks. In order to further reject the large QCD multi-jet background, additional criteria are imposed to take advantage of the distinct topology of four  $b$  jets arising from  $\phi b\bar{b}$  ( $\phi = h, H, A$ ) production. These criteria involve an  $M_\phi$  dependent cut on the  $E_T$  of the three highest- $E_T$  jets, a requirement that the azimuthal angle between the two leading  $b$  jets be larger than 1.9 radians, and an  $M_\phi$  dependent cut on the invariant mass of several different jet pairings.

Distributions in several variables used in the analysis, comparing data and SM prediction, are shown in Fig. 3 for CDF data with three  $b$ -tagged jets, prior to the imposition of the mass requirements. A breakdown of the efficiencies and backgrounds in the analysis, along with the number of observed events in the final selection is given in Table 3. No evidence for a  $\phi b\bar{b}$  signal is seen, providing a 95% C.L. limit on  $\sigma \times B$  for this process of 25.7 pb. This limit can be interpreted within the framework of the MSSM as an exclusion region in  $\tan\beta$  vs.  $M_h$  or  $M_A$  space. The excluded regions are presented in Fig. 4. As can be seen, the excluded regions extend significantly those previously probed by LEP.

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<sup>1</sup>The pseudo-rapidity,  $\eta$ , is defined as  $\eta = -\ln(\tan \frac{\theta}{2})$ , where  $\theta$  is the polar angle.



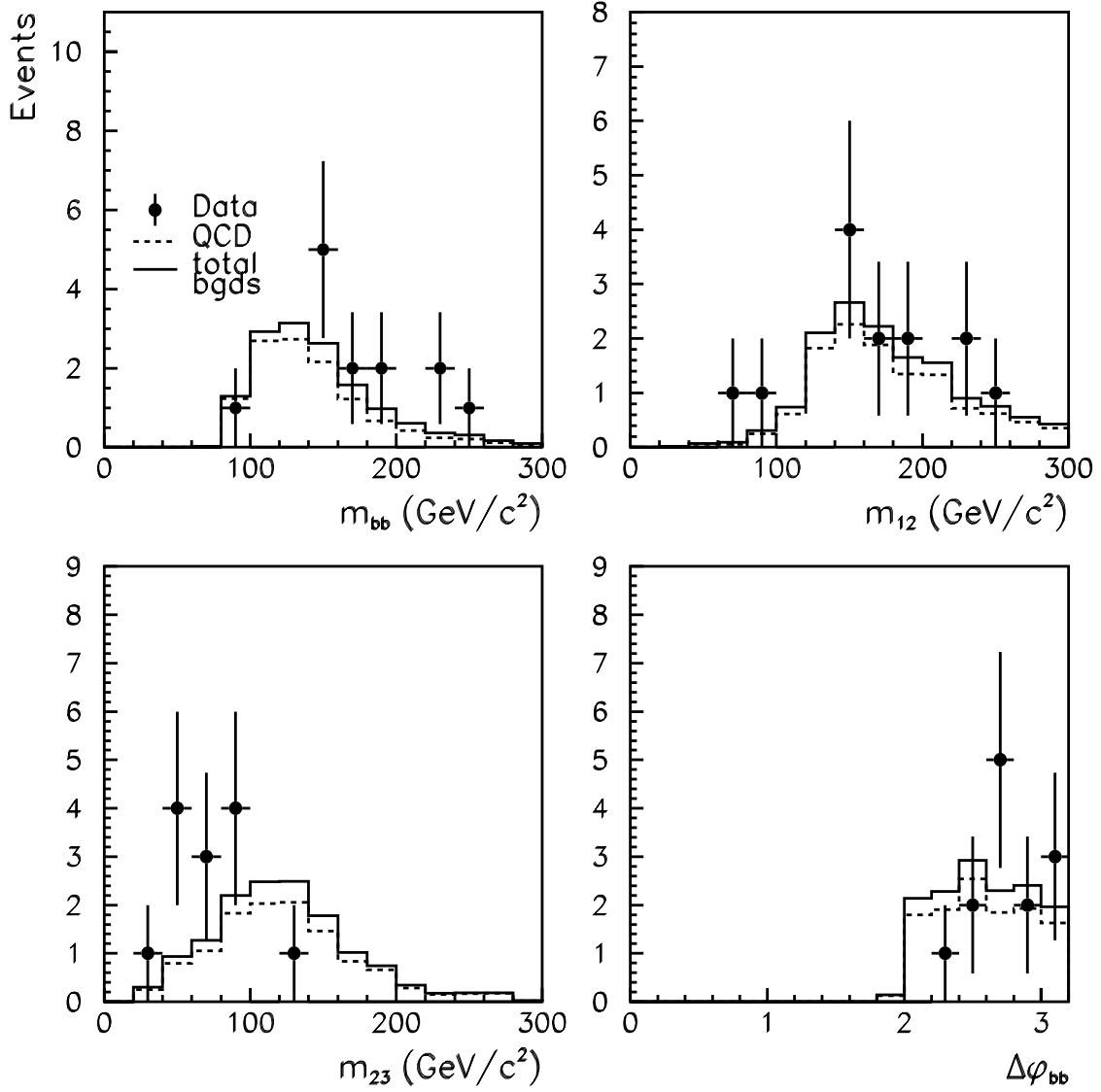


Figure 3: *Distributions of data in the 3-b selected sample for the largest invariant mass b-tagged jet pairs ( $m_{bb}$ ), the mass combination of the highest- $E_T$  and next-highest- $E_T$  jets ( $m_{12}$ ), the mass of the second- and third-highest  $E_T$  jets ( $m_{23}$ ) and the azimuthal difference between the two leading b-tagged jets ( $\Delta\varphi_{bb}$ ).*

Table 3: *Results of the preliminary CDF  $\phi b\bar{b}$  search including efficiencies at various stages of the selection process and the number of background and observed events in the final selection. Backgrounds are calculated for the  $M_\phi=100$  GeV selection and for the integrated luminosity of the data sample.*

Efficiencies			Backgrounds	
	Trigger	1.9%		
	Jet $E_T$	86%	QCD	$2.2 \pm 1.1$
	$\geq 3$ $b$ 's	20%	Fakes	$0.5 \pm 1.4$
	$\Delta\varphi_{bb}$	82%	$Wb\bar{b}/c\bar{c}$	$0.1 \pm 0.1$
	Mass	93%	$Zb\bar{b}/c\bar{c}$	$0.37 \pm 0.02$
	Total Effic.	0.25%	Total Bgrd.	$3.8 \pm 1.1$
Observed Events		3	$\sigma \times B$ Limit	25.7 pb

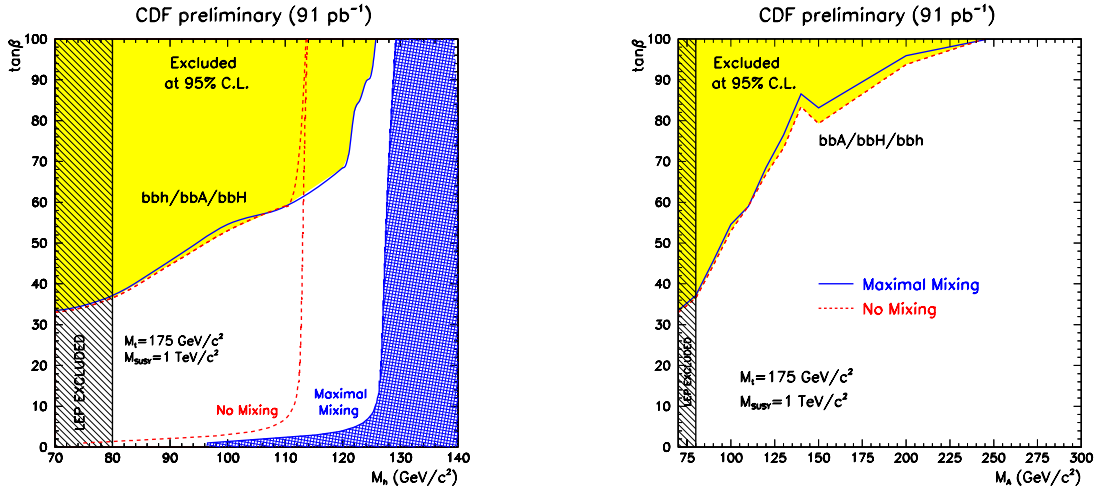


Figure 4: *The region excluded at 95% C.L. by the CDF  $\phi b\bar{b}$  analysis in  $\tan\beta$  vs.  $M_h$  (left plot) and  $M_A$  (right plot) parameter space. The double-hatched region corresponds to theoretically forbidden values of  $M_h$ . The solid line corresponds to the case of no stop-squark mixing, and the dashed line to maximal mixing.*

## 4 Higgs Searches at Run II

Despite the good sensitivity of Run I analyses to several non-SM Higgs bosons, the results for the SM Higgs are (as expected) not significant. As we saw in Table 2,  $\sigma \times B$  limits for final states expected from the SM Higgs are, at best, a factor of 50 higher than predictions. Given this picture, why are we optimistic about Higgs searches in Run II? There are three reasons: higher  $\sqrt{s}$ , higher luminosity and better detectors.

The increase in center of mass energy of the Tevatron for Run II is modest (1.8 to 2.0 TeV). This translates, however, into a substantial gain in cross section for associated Higgs production of approximately 20% in the SM.

As mentioned previously, the integrated luminosity collected in Run II is expected to be at least  $2 \text{ fb}^{-1}$  by 2002 and should reach  $\sim 15 \text{ fb}^{-1}$  before the start of the LHC. This large data set will be our main lever on the SM Higgs. However, it should not be forgotten that if we see evidence for a Higgs particle, larger control samples such as  $Z \rightarrow b\bar{b}$  that will be available in Run II will give us confidence that what we observe actually corresponds to signal.

In order to take maximum advantage of the glorious new data sets, both CDF <sup>9)</sup> and DØ <sup>10)</sup> are being upgraded. From experience with Run I analyses and some theoretical guidance, a clear picture has emerged of the most important detector properties required for Higgs searches. Missing energy, leptons and  $b$ -quarks are the experimental pillars of Higgs searches at hadron machines. Efficient identification and accurate reconstruction of these objects requires all features of the detectors to work at full capacity, and consequently all aspects are being overhauled. Some of the improvements that have the most impact on Higgs searches are mentioned below.

Improving lepton identification is mainly a question of increasing the coverage of the calorimeters for electrons (which also determines missing energy resolution) and the muon chambers for muons. The Run I calorimeters of both experiments were excellent. Therefore, no changes are being made, aside from those required to adapt to the new beam conditions. CDF and DØ are, however, both increasing the effective coverage of their muon systems.

Identification and reconstruction of  $b$ -quarks depends critically on tracking (although soft lepton identification also plays a role). To improve prospects, the old CDF silicon detector is being replaced with new 3D readout detectors that provide stand-alone silicon tracking to  $|\eta| < 2.0$ . This amounts to a 40% increase in acceptance. Using this detector, CDF expects to gain in the efficiency of double

$b$ -tagging for  $t\bar{t}$  events by a factor of 3.5<sup>25)</sup>. The tracking system of DØ will be even more radically revamped. Central to this is the addition of a magnet providing a solenoidal field of 2.0 T in the tracking volume. The tracking system will consist of cylinders of scintillating fibers and a silicon detector with 3D readout extending to  $|\eta| < 1.7$ . This will allow DØ to join in the  $b$ -quark game at the same level as CDF. Both detectors are also adding dedicated trigger systems to identify  $b$ -quarks online.

#### 4.1 Prophecies for Run II

We now embark into the realm of speculation about what will happen in Run II. This is not purely an exercise in fantasy, because it is extremely important to understand how detector limitations will affect Higgs searches while these parameters can still be modified. It is also crucial to know what luminosity is required to achieve sensitivity to the Higgs at different masses, as this will strongly influence the running strategy. As such, a Fermilab-wide working group, consisting of representatives from CDF, DØ and the Theory Group, was established to study Higgs issues at Run II. The results presented in this section are based mainly on a preliminary version of the Working Group report (version 3) available at the time of the conference. The most up to date version (version 6) can be found on the Working Group's web page<sup>13)</sup>.

Of course, to make predictions that have any chance of correctly fortelling the future we need accurate simulations of key performance parameters. Unfortunately, full simulations of the upgraded CDF and DØ detectors are still evolving. However, even with a relatively simple simulation, using parameterized detector response, we can go a long way towards answering questions that are relevant for the construction and early running phases of Run II concerning detector resolution and efficiencies required for Higgs sensitivity and luminosity limitations on the mass reach.

The simulation used for the bulk of the results presented here, referred to as SHW, parameterizes important detector resolutions and efficiencies using an "average" of the foreseen Run II CDF and DØ detectors<sup>13)</sup>. Most of the detector parameters in SHW are tunable, allowing studies to be made of how a specific parameter impacts Higgs sensitivity. As a baseline, most analyses use a track reconstruction efficiency of 97% for tracks with  $|\eta| < 2$  and  $P_T > 300$  MeV, relative energy resolutions for the electromagnetic and hadronic calorimeters of  $20\%/\sqrt{E}$  and  $80\%/\sqrt{E}$  respectively,  $b$ -tagging efficiency of  $\sim 60\%$  for  $E_T = 100$  GeV and a  $b\bar{b}$  relative mass resolution of 10–14%.

A few warnings about SHW are in order. First, since SHW is a parameterized simulation, details of event-by-event detector response are missing. This means that systematic effects and hardware-related background and misidentifications are largely neglected. Their impact can be estimated, however, from extrapolations of Run I results, and thus are not completely ignored. Another difficult issue concerns the trigger. Excellent trigger performance will be crucial to obtaining good results. The most questionable of these, the hadronic event triggers, are considered in the analyses outlined here, however, leptonic triggers are generally taken to be 100% efficient. This is a reasonable assumption if lepton triggers function as foreseen. In general, SHW predictions should be taken in their context – a means to understand the detector and accelerator requirements so as to achieve competitive sensitivity to Higgs. While more elaborate simulations may yield slightly more accurate predictions in some areas, only data will tell us the real story.

Before turning to channel-by-channel sensitivities as a function of Higgs mass and luminosity it is worthwhile to describe the SHW results concerning the key Higgs-search detector parameters: missing energy resolution, lepton identification,  $b$ -quark identification and  $b\bar{b}$  mass resolution.

1. Missing  $E_T$  resolution was excellent in Run I and no gains are foreseen in this area.
2. Lepton identification efficiency in CDF and DØ is mainly governed by geometrical acceptance. Improvements are being made in the muon systems of both detectors.
3. Tagging of  $b$ -quarks plays an important role in any Higgs search. However, signal significance ( $S/\sqrt{B}$ ) grows at a faster rate if  $b\bar{b}$  mass resolution is improved than if  $b$ -tagging efficiency is increased. This highlights the importance of a good understanding of the  $b$ -jet energy scale.

Sensitivity to an SM Higgs boson from a combination of CDF and DØ expectations, as measured by signal over the square-root of background ( $S/\sqrt{B}$ ), for various decay channels, as a function of Higgs mass, is presented in Fig. 5 for an integrated luminosity of  $1 \text{ fb}^{-1}$  per experiment. Several points are apparent. First, the mass reach of the Tevatron experiments is significantly improved by considering final states produced when the Higgs (at high mass) decays to real or virtual boson pairs. Second, good improvements in sensitivity over purely cut-based analyses can be expected when using multi-variate techniques such as neural net analyses<sup>26)</sup>. Finally, it is clear that  $1 \text{ fb}^{-1}$  per experiment will not get us to the Higgs. This

is quantified in Fig. 6 where the combined CDF and DØ 95% C.L. limits,  $3\sigma$  evidence and  $5\sigma$  discovery thresholds for a given integrated luminosity delivered to each experiment are plotted as a function of Higgs mass. With the minimal Run II integrated luminosity of  $2 \text{ fb}^{-1}$ , the Tevatron will barely, if at all, extend the expected LEP2 Higgs mass limit of  $\sim 115 \text{ GeV}$  <sup>27)</sup>. With more than  $10 \text{ fb}^{-1}$  per experiment, an SM Higgs could be excluded up to around  $180 \text{ GeV}$ . First hints of a real Higgs signal (at  $3\sigma$ ) would only appear beyond what has already been excluded for an integrated luminosity of at least  $20 \text{ fb}^{-1}$  per experiment.

An important consideration in making the projections in Fig. 6 is our confidence in the predictions for background. Estimates of background levels based purely on Monte Carlo are notoriously unreliable; especially those originating from tails of distributions. An example is the QCD  $b\bar{b}$  background in the  $\nu\bar{\nu}b\bar{b}$  channel. To take account of this unreliability, a relative uncertainty on the background ( $B$ ) in each channel of a minimum of 10% or  $1/\sqrt{LB}$  (where  $L$  is the integrated luminosity) is used in combining the individual channels to produce Fig. 6. Of course, the increased luminosity of Run II should provide better understanding of the background based on control data samples, which can be used to tighten selection criteria, thereby reducing background systematics.

Projected sensitivities for both neutral and charged Higgs in the framework of the MSSM <sup>13)</sup> indicate that a relatively high integrated luminosity ( $10\text{--}15 \text{ fb}^{-1}$  for exclusion or  $20\text{--}30 \text{ fb}^{-1}$  for discovery) will also be needed to reach decisive conclusions. However, if this is delivered, SUSY could be discovered or constrained over significant regions of the MSSM parameter space.

## 5 Conclusions

As we have seen, the Tevatron has been a very active field for Higgs searches. Several interesting limits have come out of Run I analyses relevant to predictions beyond the SM, but results for the minimal Higgs have not dented the SM. Nevertheless, the valuable experience gained in Run I, is already being applied to the upcoming Run II, slated to start in March of 2001. In order to have the best possible detectors for Higgs searches and to help set optimal parameters for the next run, studies have been initiated by the Fermilab Run II Higgs Working Group to determine the effect of detector choices and luminosity on the Higgs reach at the Tevatron. The main improvement in Run II that makes us optimistic about Higgs prospects is certainly the increased luminosity, a factor of 20 or perhaps as much as 300 over that delivered in Run I. Detector improvements will also play a big role. The main gains

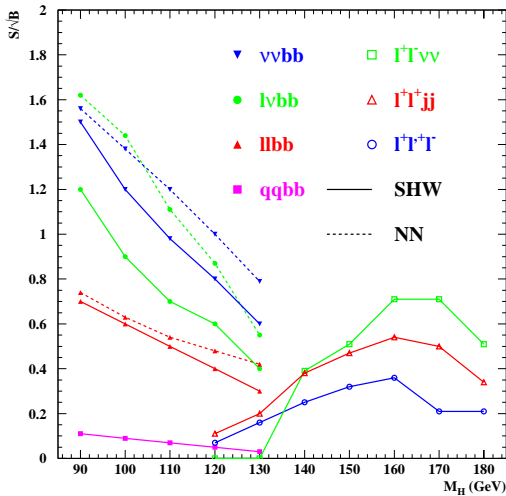


Figure 5: *Sensitivities for a combination of CDF and DØ expectations in the main SM Higgs final states. Results are given for  $1 \text{ fb}^{-1}$  delivered to each experiment. Points connected by solid lines correspond to cut-based analyses, while the dashed lines indicate results using a neural nets.*

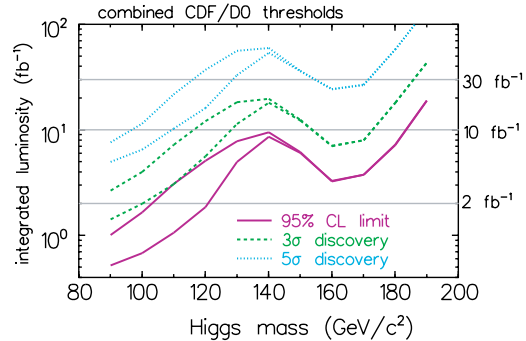


Figure 6: *SM Higgs sensitivity predicted for a combination of CDF and DØ expectations as a function of Higgs mass and integrated luminosity delivered to each experiment. Limits (at 95% C.L.),  $3\sigma$  evidence and  $5\sigma$  discovery curves are plotted for cut-based (upper lines) and neural net-based (lower lines) analyses.*

here come in  $b$  identification and  $b\bar{b}$  mass resolution – both of which are essential for discovering the Higgs. Not to be overlooked is the fact that DØ will fully enter the arena of  $b$ -tagging with their upgraded tracking system in Run II. This will have a major impact on the overall Tevatron sensitivity. The big lesson that Run II Higgs prophecies teach us though is that luminosity will be crucial. With only the initial  $2 \text{ fb}^{-1}$  the Tevatron will not extend the eventual LEP2 Higgs sensitivity, of  $\sim 115 \text{ GeV}$  <sup>27)</sup>. With  $10 \text{ fb}^{-1}$  we could exclude at 95% C.L. an SM Higgs up to  $\sim 180 \text{ GeV}$  and with  $20 \text{ fb}^{-1}$  we could see evidence at the  $3\sigma$  level for Higgs masses up to  $180 \text{ GeV}$ . Similarly, strong sensitivity to a wide region of MSSM parameter space can be made with more than  $10 \text{ fb}^{-1}$ . These sensitivities are especially interesting given that the lightest Higgs is predicted to lie below  $\sim 130 \text{ GeV}$  in the MSSM. Needless to say, anticipation at the Tevatron is high!

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